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Superconducting accelerator magnet technology in the 21st century: A new paradigm on the horizon?

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ABSTRACT

Superconducting magnets for accelerators were first suggested in the mid-60's and have since become one of the major components of modern particle colliders. Technological progress has been slow but steady for the last half-century, based primarily on Nb–Ti superconductor. That technology has reached its peak with the Large Hadron Collider (LHC). Despite the superior electromagnetic properties of Nb_3Sn and adoption by early magnet pioneers, it is just now coming into use in accelerators though it has not yet reliably achieved fields close to the theoretical limit. The discovery of the High Temperature Superconductors (HTS) in the late '80's created tremendous excitement, but these materials, with tantalizing performance at high fields and temperatures, have not yet been successfully developed into accelerator magnet configurations. Thanks to relatively recent developments in both Bi-2212 and REBCO, and a more focused international effort on magnet development, the situation has changed dramatically. Early optimism has been replaced with a reality that could create a new paradigm in superconducting magnet technology. Using selected examples of magnet technology from the previous century to define the context, this paper will describe the possible innovations using HTS materials as the basis for a new paradigm.

1. Introduction

One of the first references to the use of superconducting magnets for accelerators was in a paper by Blewett, published in 1965 [1]. The primary challenges were in achieving the current in the magnet based on a measurement of a short sample of the conductor independent of the coil geometry. The concept of current sharing cables was proposed by Stekly and Zar [2], an important step in the continued development of superconducting magnets in general. It is still an important performance aspect and, as will be discussed in the section on HTS magnets, a continuing challenge today. Unquestionably, the most influential event was the Brookhaven Summer Study in 1968 [3] where many important topics were discussed, including one of the most critical aspects of conductor performance; the relationship between strand diameter and stability against flux jumps.

Nb_3Sn and Nb–Zr were early candidates for magnet conductor. However, the brittleness of Nb_3Sn and the high temperature heat treatment that was required to create the superconducting phase, proved to be too much of a challenge in the early days of magnet development and despite having superior superconducting properties, the R&D community focused primarily on Nb–Ti. Only in the very late 20th century has Nb_3Sn become a viable candidate for accelerator magnets. Nb–Zr was abandoned in 1967 due to the inability to produce an alloy with consistent properties.

In the late 1980's, the discovery of the High Temperature Superconductors (HTS) jolted the magnet R&D community. For High Energy Physics (HEP) applications the interest was more in the high field performance of the conductor rather than the higher operating temperature where the current density was lower. There were serious suggestions to halt development of the 6.6 T Nb–Ti dipoles for the Superconducting Supercollider (SSC) and focus on HTS. As we know, cooler heads prevailed and that was not the case. As hindsight has revealed, this would have been a devastating technology choice at the time. The failure of the SSC was not due to technological issues!

There are two primary HTS materials that are sufficiently mature enough for the next step of magnet development; rare-earth barium copper oxide (REBCO) tapes (Fig. 1) and Bi-2212 round strands (Fig. 2). Iron-based superconductors [4] are on the horizon, and with a breakthrough could be a candidate within the next decade or so. REBCO has been successfully used to reach fields over 35 T in solenoids [5] and has achieved engineering current densities exceeding 1000 A/mm^2.

The excitement over HTS, particularly for accelerator magnet applications, died rapidly due to the respective challenges in fabricating practical magnets. However, since their discovery 3 decades ago, development and investment by the Office of Energy Efficiency and Renewable Energy (EERE) and the DOE Office of High Energy Physics (OHEP) has resulted in superconductors that can now be considered for high field accelerator magnets. Current densities in these two conductors now rivals or exceeds the low temperature superconductors (LTS) at high field making them the only choice for magnets beyond the practical limit of Nb_3Sn. Fig. 3 illustrates the reason why magnet developers are turning their attention to HTS. There are now serious efforts in the

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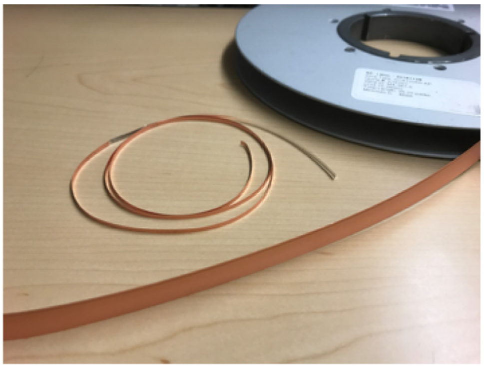


Fig. 1. Two commercial tapes from SuperPower: 12 mm wide, 100 μm thick tape and 2 mm wide, 45 μm thick tape.

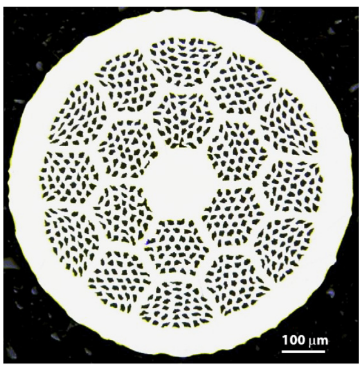


Fig. 2. Bi-2212 strand cross section.

US and EU to exploit the properties of HTS for high field accelerator magnets while mitigating the limitations. Utilizing the potential that HTS promises calls for an overall approach quite different from that used for LTS over the past half-century and could usher in a new paradigm for accelerator magnet technology. We begin with selected examples of LTS magnet technology in order to define the context for comparison with the challenges and potential of magnets built with HTS conductors.

2. Nb–Ti technology

The success of Nb–Ti over other candidate superconducting magnet materials was significantly enhanced by a number of developments that took advantage of the ease of fabrication compared with Nb_3Sn despite a lower potential for achieving high fields. In 1971, a short paper described a "compacted fully transformed cable" produced at Rutherford Lab [6]. Now known as "Rutherford cable", this innovation transformed the accelerator magnet world and has been used in every successful accelerator magnet built to date. The basic enabling components of superconducting accelerator magnet technology were in hand, and in the 1970's a number of projects were launched. Among them were the ill-fated ISABELLE at Brookhaven [7], IR quadrupoles for the ISR at CERN [8], TRISTAN at KEK [9], the UNK storage ring in the USSR [10] and the Fermilab Energy Doubler (now referred to as the Tevatron) [11,12]. Since the Tevatron (1983), through HERA (1991) [13] , RHIC (2000) [14] and finally the LHC (2008) [15] all large-scale hadron colliders were built using superconducting magnets based on Nb–Ti.

2.1. Tevatron

The rise of the application of superconductivity for accelerators was triggered by the success of the Tevatron, a collider for protons and anti-protons built at Fermilab. The Tevatron contained over 700, 6.1 m dipoles, with a 76 mm aperture operating at 4.6 K and 4.3 T, Fig. 4. There were several notable advances pioneered by the Tevatron that later led to HERA, RHIC and the LHC. The Tevatron used the first full-scale magnets based on Rutherford cable, now a standard for accelerator magnets and drove the industrialization of Nb–Ti strand, eventually leading to a market based on MRI that now far exceeds the needs of HEP. Another major contribution was the introduction of collars to apply the required pre-stress to react against the Lorentz forces and prevent driving the conductor normal.

2.2. HERA

During construction of the Tevatron, the DESY laboratory in Hamburg embarked on the design of an electron–proton collider based on dipoles with aperture and field similar to the Tevatron (75 mm and 5 T), Fig. 5. As opposed to the Tevatron dipoles that used a warm iron yoke, the HERA dipoles used cold iron, trading alignment issues for a larger cold mass and differential thermal expansion between the coil and support structure. The HERA strand had higher current density than the Tevatron but at the expense of larger filaments that created persistent currents affecting machine operation. This discovery drove future conductor development toward smaller superconducting filaments. HERA took the important step in industrializing magnet production, a non-trivial challenge.

2.3. SSC

The SSC was set to be the world's largest and most energetic particle accelerator. The ring circumference was 87.1 km (54.1 mi) with an energy of 20 TeV per proton. It would have greatly surpassed the current record held by the Large Hadron Collider which has a ring circumference of 27 km (17 mi) and energy of 6.5 TeV per proton. The dipole magnets, Fig. 6, had a 50 mm bore and an operating field of 6.6 T at 4.5 K [16]. The project was canceled in 1993 due to budget problems.

2.4. RHIC

After the closing of the SSC, BNL used the tunnel originally planned for ISABELLE to build the Relativistic Heavy Ion Collider (RHIC). The tunnel was actually larger than what would originally be required for the machine, giving the magnet designers the flexibility to develop lower field (3.5 T) magnets at a lower cost. This was achieved by using a single-layer coil with the iron close to the coil, thereby providing 30% of the bore field. A cross section of the cold mass is shown in Fig. 7. They were also able to take advantage of the high-performance strand produced in the SSC R&D program. Similarly to HERA, the magnets were produced in industry.

2.5. LBNL D19

Training, the process by which a magnet climbs toward the predicted short sample current, was and still is a major concern for magnet performance. The LBNL D19 magnet design and performance is summarized here as one of the few examples of a magnet that exhibited very little training behavior.

In 1993, the same year that the SSC was canceled, LBNL built a dipole utilizing a unique support structure based on a very thin stainless-steel collar and an elliptical iron yoke as an alternative to the existing SSC dipole [17]. It had a 50 mm bore and identical 30 and 36 strand cables. The structure, designed for 10 T used a collar that provided only 10 MPa of pre-stress. The full pre-stress of 70 MPa was given by the iron yoke as opposed to the mainstream design at the time that used thick, stiff collars to generate and maintain pre-stress. The yoke was designed with a vertical, tapered gap controlled by an aluminum spacer to ensure that after cooldown there was no loss of pre-stress and the gap remained closed during full excitation. The cross section is shown in Fig. 8.

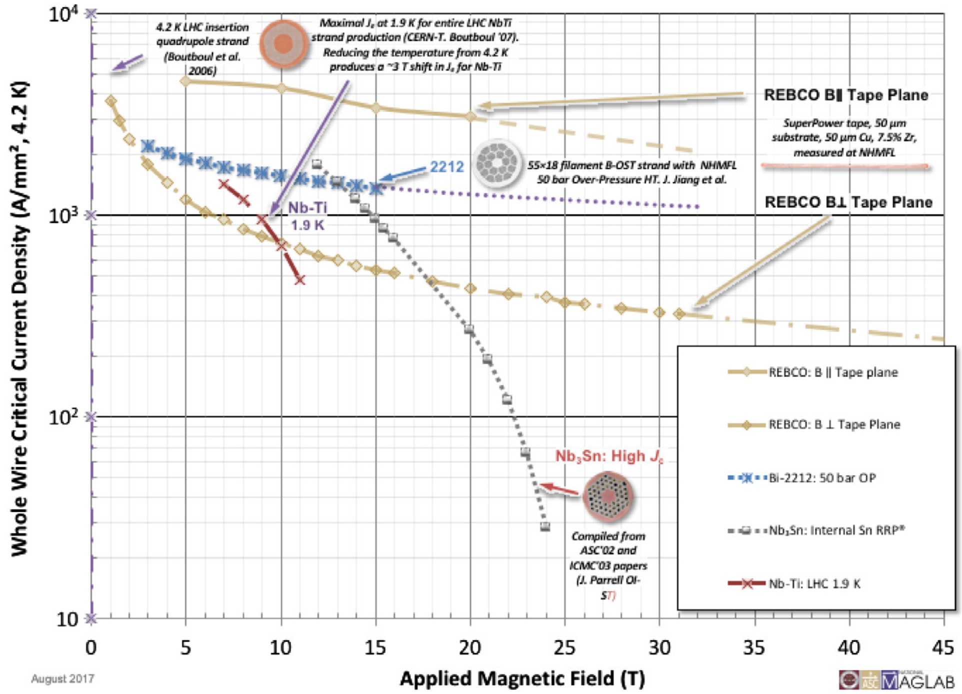


Fig. 3. Whole wire critical current density (J_e) of accelerator magnet conductors as a function of external magnetic field.
Source: Courtesy of Peter J. Lee, Applied Superconductivity Center, Florida Statue University and the National High Magnetic Field Laboratory.

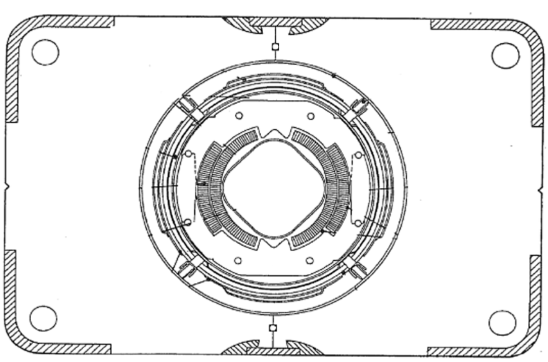


Fig. 4. Tevatron dipole cross section.

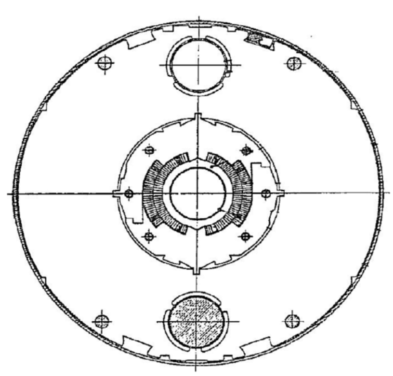


Fig. 5. HERA dipole cross section.

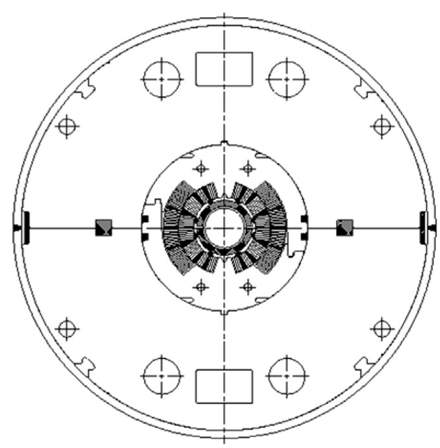


Fig. 6. SSC dipole cross section.

The training history is shown in Fig. 9. On the initial quench at 4.35 K the magnet reached 7.6 T, nearly the short sample limit. The magnet retrained starting at 95% of short sample after a thermal cycle to room temperature and on subsequent thermal cycles was extremely reproducible. At 1.8 K the magnet reached a record field of 10.06 T after 9 quenches.

2.6. LHC

The idea of building a proton–proton collider at CERN by replacing the magnets in the existing LEP ring originated in the mid 1980's. The magnet technology was gathered and integrated on the experience of previous machines. The main features of the Nb–Ti LHC magnets were:

- Collars and cold iron yoke.
- Two-in-one design introduced for ISABELLE.
- The high-performance strand specification based on the SSC.
- Implementation of 1.9 K cooling on a large scale to maximize the field.

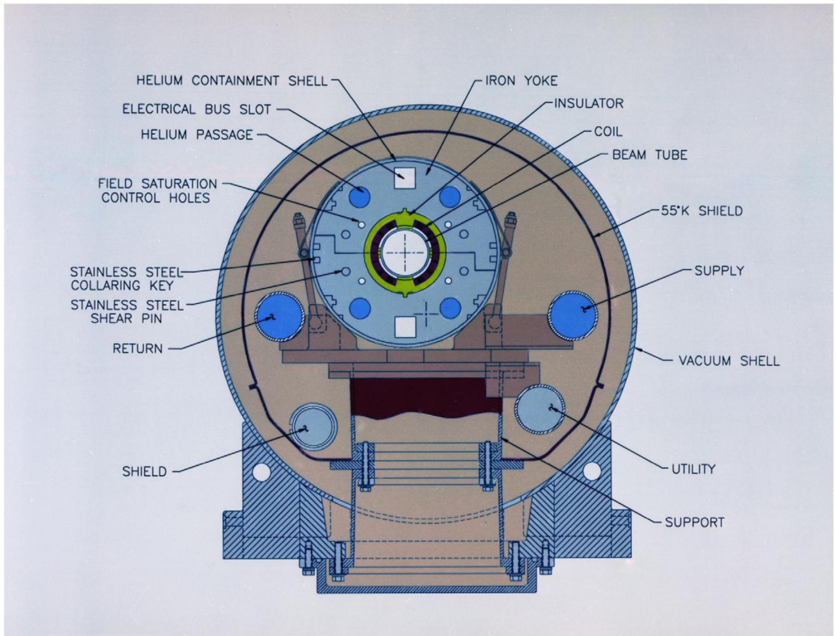


Fig. 7. RHIC dipole.
Source: Courtesy of P. Wanderer, BNL.

The cross section of the LHC dipole is shown in Fig. 9. Cooling to 1.9 K increases the upper critical field of the conductor by about 3 T and the dipoles were designed to operate at 8.33 T, equivalent to 7 TeV per beam in the LHC. The dipoles were produced by 3 industrial firms with the result that there was a systematic difference in performance that depended on the vendor. At this time, the energy of the machine is limited to 6.5 TeV, just below nominal, due to the necessity of retraining the dipoles after warm-up. More details can be found in [18].

3. Nb_3Sn technology

While the challenges of Nb_3Sn dampened progress relative to the ductile but lower field Nb–Ti, a few programs in the USA, Europe and Japan continued development started in the '60's through the 1980's. Early magnets used available Nb_3Sn tapes but later turned to filamentary composite strands produced by the "bronze route" process. The performance of these strands was superior to Nb–Ti at high fields and were more stable than tape conductors due to the small diameter of the filaments. Of particular note during this time, the ISABELLE project was developing 5 T Nb–Ti dipoles and in parallel, Nb_3Sn dipoles with the same cross section using a react and wind technique to avoid reacting large coils and allowing the use of standard insulation. Both designs were based on a multi-strand braided cable [19,20]. A slightly modified version of the dipole reached 4.8 T which was very close to the short sample limit. Nb_3Sn conductor continued to improve, creating the possibility for magnets operating beyond the Nb–Ti limit of 10 T. Based on the Tevatron experience, Rutherford cable became the new standard. In the early '80's a dipole, developed and tested by CEA Saclay [21], and a quadrupole at CERN [22] drove the technology forward. One of the first attempts to maximize the high field potential of Nb_3Sn was made at the Lawrence Berkeley National Laboratory (LBNL) where they designed and tested a dipole aimed at achieving 10 T [23–25]. This magnet used an improved conductor based on the Internal Tin process with much higher current density than the bronze route conductor. At 4.2 K the magnet reached 8 T after a number of training quenches, short of the conductor limit, possibly due to conductor motion or heating of the lead splices.

It was not until the later part of the 20th century that the accelerator magnet R&D community returned to the challenge of Nb_3Sn, driven by the desire for higher fields and was able to break the 10 T barrier and start to tap the field potential of Nb_3Sn.

3.1. Twente University MSUT

In 1996, a 50 mm aperture, cos-theta type model dipole, built by the University of Twente and tested at CERN reached 11 T on the first quench at 4.4 K [26]. The magnet, an experimental version of an LHC dipole (Fig. 10), incorporated several interesting features. The strand, based on the Powder-in-Tube (PIT) approach, had at that time a non-Cu current density between 1000 and 1500 A/mm^2 at 12 T and 4.4 K but was further reduced due to degradation of the 33 strand cables which were the largest produced at that time. The team also introduced a winding technique that provided continuous support in the transition from body to the ends. The coils, following reaction, were epoxy impregnated and collared using shrink-fitted ring-shaped collars around the coils.

3.2. LBNL Nb_3Sn program

The high field magnet program at LBNL took a more ambitious approach to the development of high field accelerator magnets in the early 90's. In 1996, D20, a 4-layer Nb_3Sn cos-theta dipole modeled after the successful Nb–Ti D19 (see Section 2.5) reached 12.8 T at 4.4 K and 13.5 T at 1.8 K [27]. At that time, D20 was considered a tour de force, not only breaking the field record of the MSUT dipole by 2.5 T but also the development of an integrated design approach that included multi-phase heat treatment, thermal expansion of materials, protection heaters, epoxy impregnation, and application of sufficient preload. All of this was accomplished without many of the design tools we take for granted today. One of many unique features of the magnet was the use of wire-wrapping for preload. Eighteen layers of rectangular stainless-steel wire were wound around the yoke with a tension of 500 N, Fig. 11. A delicate procedure indeed!

D20, though an unequivocal success took almost 6 years to complete and was considered a "near-miss" by the Department of Energy (DOE).

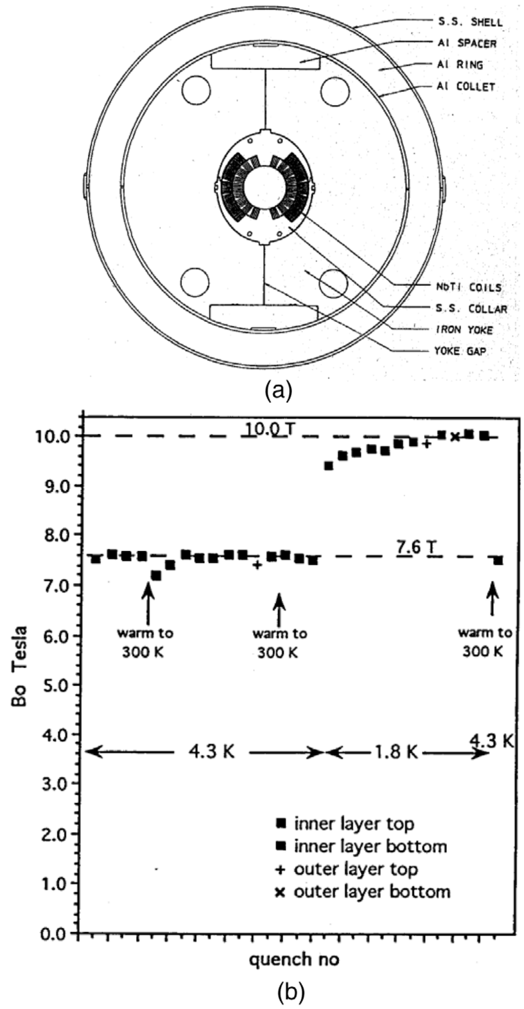


Fig. 8. (a) D19 cross section. (b) D19 training history.

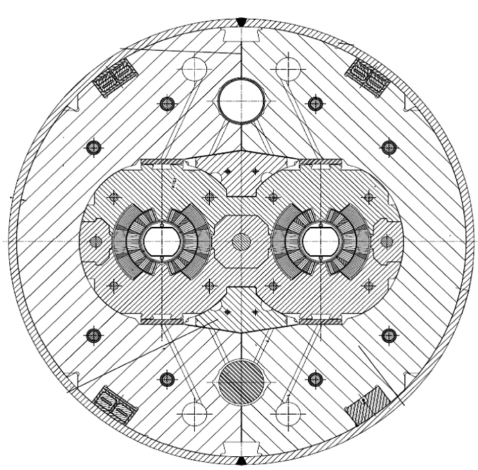


Fig. 9. LHC dipole cross section.

The small but important details that are critical for later success of an R&D program are sometimes overlooked by risk averse funding agencies. Taking the lessons learned from the D20 project, the program embarked on a new development path that emphasized simplicity and an incremental approach. The core of this program was based on simple

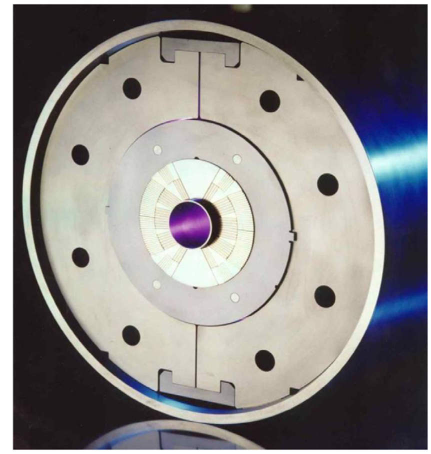


Fig. 10. University of Twente MSUT dipole.
Source: Photo courtesy of H. ten Kate, U. Twente and CERN.

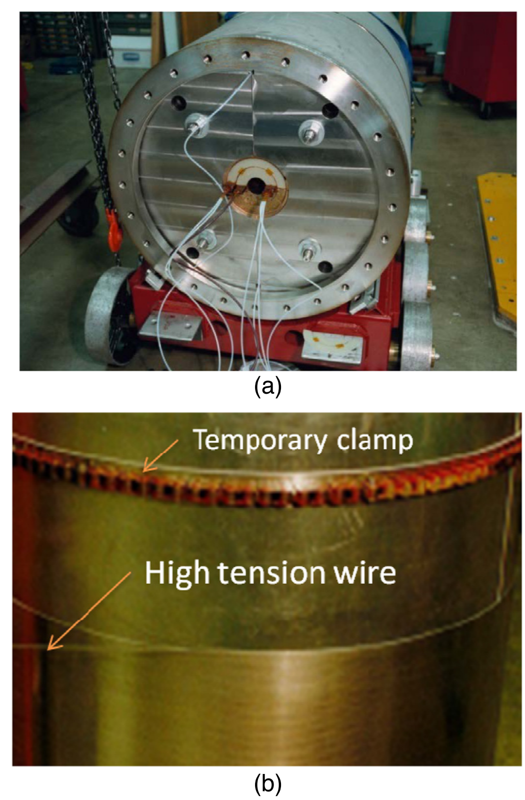


Fig. 11. (a) D20 non-lead end before installing the end plate. (b) Close-up of the wire wrap.

racetrack coils using a double-pancake winding that simplified the lead geometry and avoided internal splices. These coil modules could be powered in a common coil, dipole or quadrupole configuration. Another aspect of the revamped program was the development of a simpler structure better suited to a n R&D environment. In the course of pursuing a new structure, it was found that small, simply constructed magnets, referred to as "sub-scale" magnets, using racetrack coils, could provide a rapid prototyping platform for dedicated studies. A number of simple models were built as precursors to the first attempt at achieving high fields using a newly developed support structure.

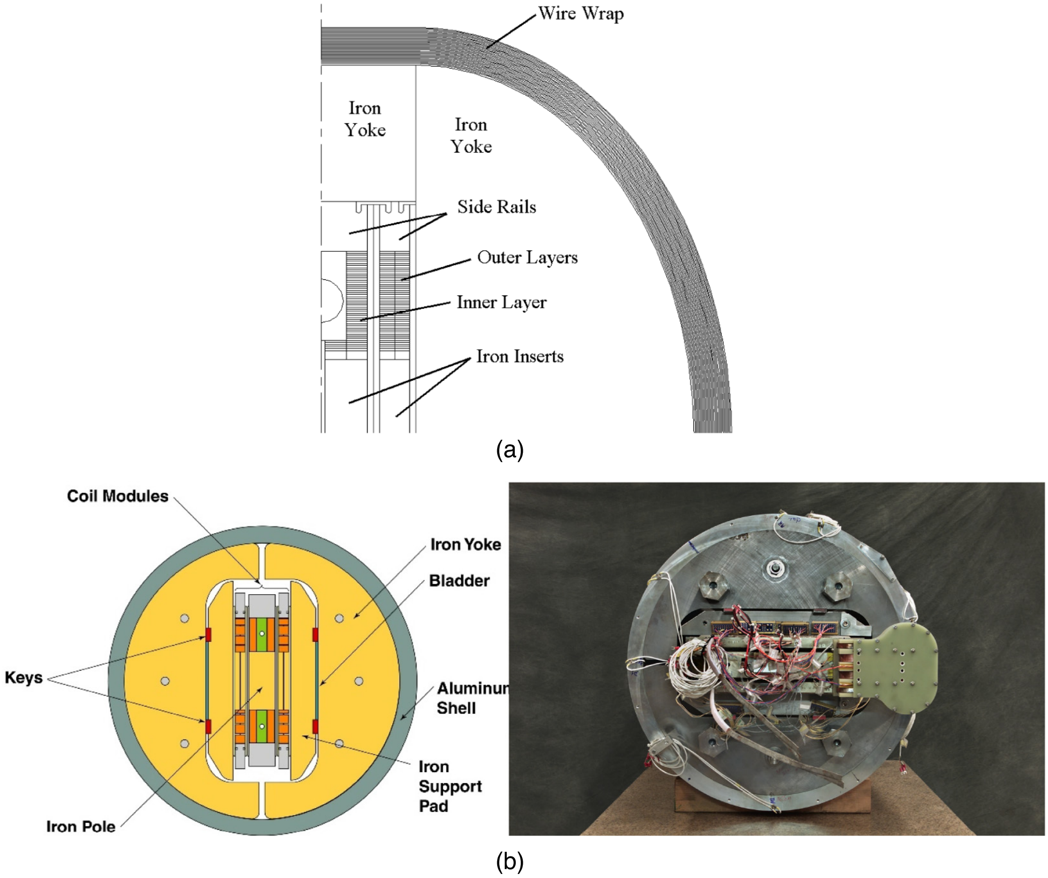


Fig. 12. (a) Original design of RD-3 using a wire wrap support structure technique and (b) cross section of the final design of RD-3 based on the key and bladder concept with a 10 mm bore and the completed magnet.

RD-3, shown in Fig. 12, used two previously tested coil modules with a new inner module in an attempt to reach fields on the order of 14 T. Though the wire wrap method was successfully demonstrated on D20, it was felt by many in the group that the process was much too complicated and time consuming. At the time, there were no alternatives. The bolted structure used for the previous lower field magnets could not supply the required preload. Coil separation in this case could not be tolerated. Expanding on a concept used successfully on the VENUS ECR ion source at LBNL a structure based on bladders to provide preload and maintained by keys was developed [28,29]. This technique gave the engineers excellent control over the pre-stress applied to the coils. This preload technique has now been widely adopted by the R&D community and is used for the quadrupoles now being constructed for the LHC IR upgrade. On the initial test, the magnet reached 14.2 T but voltage signals indicated that the quenches were still motion induced. On the first thermal cycle the magnet achieved the previous field on the first quench, showing excellent retention of training. During this test the magnet reached 14.7 T, near the short sample limit. More details on RD-3 can be found in [30].

Development of the key and bladder concept was done using a 1/3 scale mechanical structure. It was quickly realized that this would make an excellent R&D vehicle for a large number of parametric studies at a much higher rate and lower cost. One of the sub-scale magnets is shown in Fig. 13. Details of this program and results can be found in [31–34].

The next step after the successful test of RD-3 was to increase the complexity and take a step toward a practical accelerator magnet by introducing a 35 mm bore and field quality. RD-3c, shown in Fig. 14, reached a plateau at 10.9 T, 92% of the un-degraded short sample prediction [35].

Following the development of the RD-series based on the common coil design, the group resumed the pursuit of higher fields using block

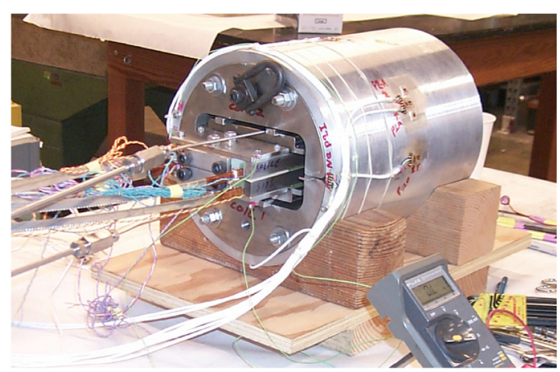


Fig. 13. Sub-scale magnet assembly.

coils. The High Field Dipole (HD) series began with two flat double pancake coils that would explore the stress limits of Nb_3Sn. The first magnet in the series, HD-1, Fig. 15, achieved a field record of 16 T at 4.4 K [36,37].

Buoyed by the success of HD-1 the program focused on incorporating the main design features required for high energy collider applications: HD-2 had a magnetically efficient layout; a clear aperture in the 40 mm range; a cost-effective fabrication process; and high field quality over the full operating range from injection to high energy [38–40]. Shown in Fig. 16, HD-2 reached 15.2 T after 12 quenches. The estimated short sample was 16.5 T based on measurements of strands extracted from the cable.

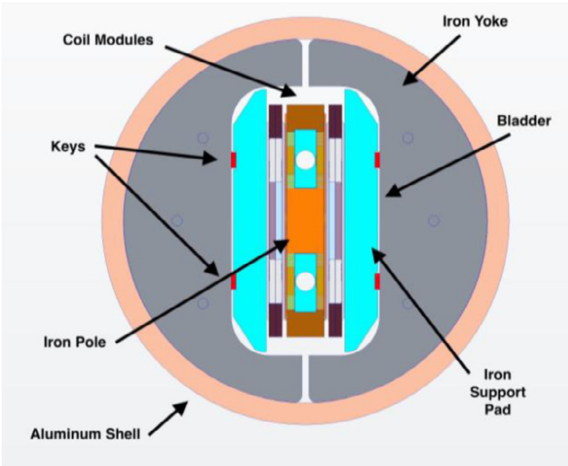


Fig. 14. Cross section of RD-3c.

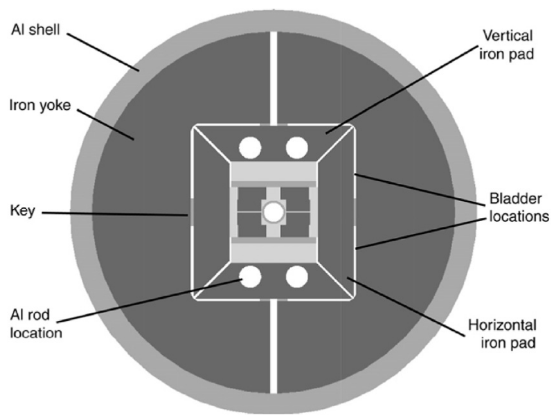


Fig. 15. Cross section of HD-1.

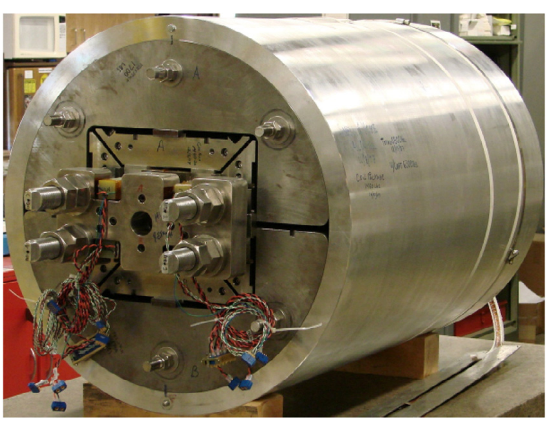


Fig. 16. HD-2.

3.3. FNAL program

The High Field Magnet (HFM) Program at Fermi National Accelerator Laboratory (FNAL) has been developing Nb_3Sn superconducting magnets, materials and technologies for present and future particle accelerators since the late '90s. The early program was aimed at developing 10–11 T dipoles operating at 4.5 K for the Very Large Hadron Collider (VLHC), a US-proposed follow-on to the LHC. Two designs

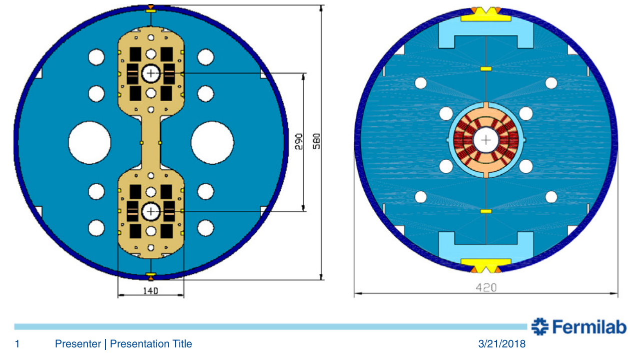


Fig. 17. VLHC magnet designs. Single-aperture cos-theta (left) and Common Coil (right).

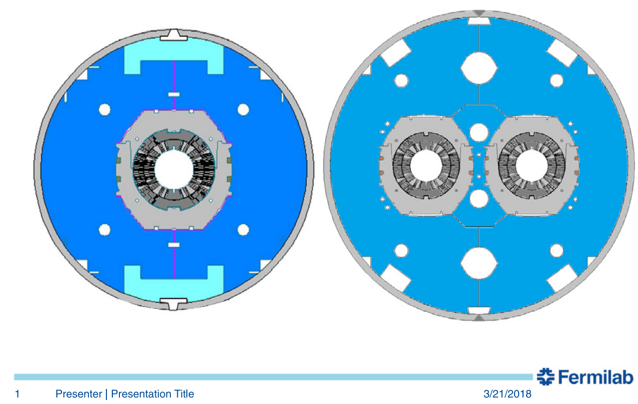


Fig. 18. Single-aperture MBHSP (left) and twin-aperture MBHDP (right) designs of the 11 T dipole.

were explored; a single aperture cos-theta using wind-and-react and a common coil based on react-and-wind [41], Fig. 17.

Based on the growing confidence in Nb_3Sn magnets generated by the success of the US R&D programs and particularly the LHC Accelerator Research Program (see Section 3.6), FNAL, in collaboration with CERN, embarked on the development of a twin aperture 11 T dipole for a special application in the LHC [42], Fig. 18. A 2-m long single-aperture Nb_3Sn dipole demonstrator was fabricated and tested at FNAL in June 2012. Two more models of an improved design reached 11.6 T or 97% of the 12 T design field. The two tested 1-m long collared dipoles were successfully tested at FNAL in February 2014 reaching 11.5 T at 1.9 K. The technology was transferred to CERN where they are now producing several magnets planned for the LHC High Luminosity Upgrade [43].

3.4. BNL program

The magnet program at BNL continues the legacy in Nb_3Sn established years ago with a program devoted to development of the common coil dipole. Due to the inherently large bend radii made possible by this design, the BNL team was able to use the react and wind technique to build and test a model dipole that reached the short sample limit of 10.2 T [44], Fig. 19. The 31 mm horizontal spacing and 338 mm vertical opening make it possible to test flat racetrack coils in a high background field. A recent study produced a relatively simple design capable of reaching 16 T [45], Fig. 20.

3.5. Texas A&M program

The Texas A&M program is based on high field, high current density, wind and react coils using internal structures to limit coil stress. The

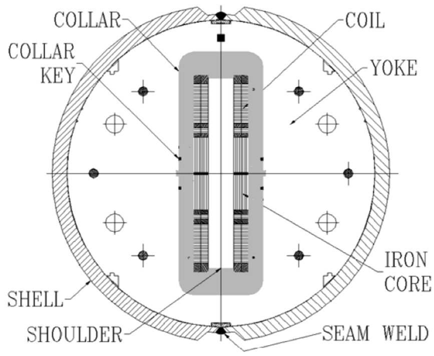


Fig. 19. BNL 10 T react and wind Common Coil.

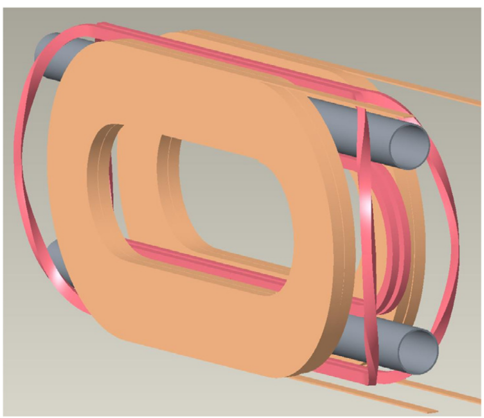


Fig. 20. BNL 16 T Common Coil Dipole Design.
Source: Courtesy of R. Gupta, BNL.

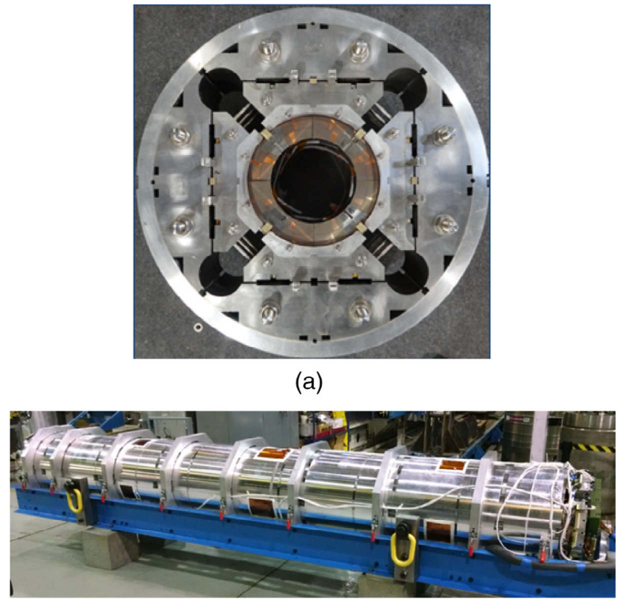
first Nb_3Sn model was built using ITER conductor, which has a lower current density than high-performance conductor of the final version but enabled them to evaluate reaction and impregnation procedures. A series of magnets of increasing complexity was planned with the ultimate goal to achieve 12 T without stress concentration, minimal deflection at shear interfaces, and uniform preload that is maintained through cool-down. One of the magnetic features of the design is an inter-layer ferric plate, intended to significantly reduce snap-back.

3.6. US LHC Accelerator Research Program (LARP) and Hi-Lumi

The three US laboratory programs, BNL, FNAL and LBNL combined resources in 2003 to create the LARP collaboration to develop technology for the improvement of the LHC accelerator complex. The magnet portion of the program (approximately half in the early years) was focused on R&D toward a high gradient, large aperture Nb_3Sn quadrupole for an upgrade of the LHC IRs [46,47]. Parameters for the LARP/Hi-Lumi quadrupole MQXFA are shown in Table 1. The quadrupole produced by LARP is one of the key technologies for the High Luminosity upgrade of the LHC (Hi-Lumi). Fig. 21 shows the cross section and a 4 m prototype. The first 4-m (MQXFAP) magnet is being tested at this time.

3.7. Future accelerator magnet R&D

High energy physicists are now asking, "what is the next step after the LHC?" CERN has answered that question by proposing a proton–proton collider with a center of mass energy of 100 TeV [48]. This massive accelerator, referred to as the Future Circular Collider (FCC),



(a)

(b)

Fig. 21. (a) The LARP/Hi-Lumi quadrupole cross section and (b) a 4 m long prototype.
Source: Photos courtesy of G. Ambrosio, FNAL.

Table 1
LARP/Hi-Lumi quadrupole parameters.

Parameter	Unit	MQXFA
Coil aperture	mm	150
Magnetic length	m	4.2
N. of layers		2
N. of turns inner/outer layer		22/28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nom. current	T	11.4
Stored energy at nom. current	MJ/m	1.2
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid-thickness	mm	1.525
Keystone angle		0.4

would be 100 km in circumference using Nb_3Sn dipoles operating at 16 T, almost twice the energy of the Nb–Ti magnets currently operating in the LHC. Depending on near-term physics results coming out of LHC, another possibility would be to double the energy of the LHC, the High Energy LHC (HE-LHC) [49].

There are currently three programs working on development of 16 T Nb_3Sn magnets. First, the WP5 EuroCirCol Program is exploring different magnet design options. Second, a CERN-led support program that includes conductor development and the electromechanical characterization of magnet components as well as the manufacture of R&D magnets. And third, the recently formed U.S. Magnet Development Program (US MDP) a broader, more generic program with a 16 T R&D component.

3.7.1. EuroCirCol

The EuroCirCol program [50] brings together CEA, CERN, CIEMAT, INFN, KEK, the University of Geneva, the Technical University of Tampere (TUT) and the University of Twente (UT) to explore different design options for 16 T dipole magnets as a baseline for future development. The results will be the core of the FCC Conceptual Design Report (FCC-CDR) to be delivered by the end of 2018. The design options under study

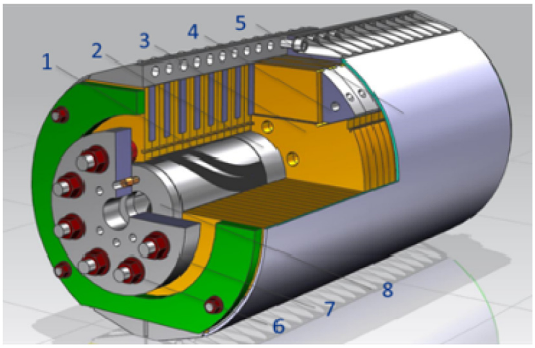


Fig. 22. MDP 4-layer 15 T cos-theta demonstrator dipole.
Source: Courtesy of A. Zlobin, FNAL.

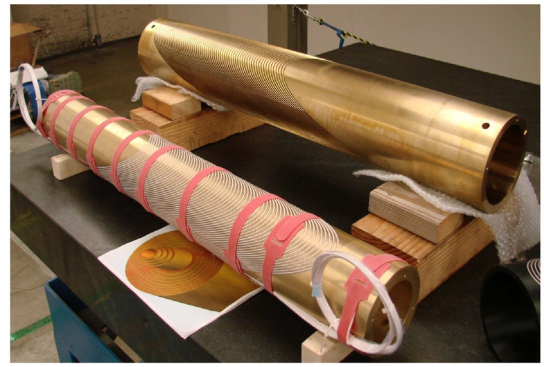


Fig. 23. MDP CCT dipole prototype.

are block-coil (CEA), common-coil (CIEMAT) and cos-theta (INFN). A fourth option, of the Canted-Cosine-Theta (CCT) type, is also being explored thanks to a contribution of PSI. All options are developed under the same set of design/performance parameters.

3.7.2. CERN 16 T magnet technology program

The 16 T Magnet Technology Program, managed by CERN, coordinates the technological support of the design and development of the 16 T dipole magnets for the FCC and the HE-LHC. The main targets of the program are to improve the state of the art conductor performance, to demonstrate the feasibility of achieving 16 T in a practical magnet, to develop the basic magnet technology (grading and splicing, instrumentation), to explore and optimize the performance (including training and field quality) with tailored R&D magnets, and finally to design, manufacture and test short model magnets. Most of these activities are carried out in collaboration between CERN and partner institutes. In particular, for the conductor development, agreements have been established between CERN and KEK (Japan), the Botchvar Institute (Russia) and KAT (Korea), and for the short model magnets agreements are being finalized between CERN, CEA (France), CIEMAT (Spain) and INFN (Italy).

3.7.3. U.S. magnet development program

Along with other international activities, in the US, the recent Particle Physics Project Priority Panel (P5) [51] has strongly supported a future high-energy proton–proton collider as part of an overall strategy. Subsequently, the DOE Office of High Energy Physics commissioned a HEPAP (High Energy Physics Advisory Panel) subpanel [52] to advise on medium and long term national goals for US Accelerator R&D in accelerator-based particle physics consistent with the P5 report. In response to the P5 and HEPAP sub-panel recommendations the DOE Office of High Energy Physics created the US Magnet Development Program (MDP) [53]. The initial program is formed around three US superconducting materials and magnet programs: Lawrence Berkeley National Laboratory, Fermi National Accelerator Laboratory and the National High Magnetic Field Laboratory/Florida State University. The MDP has 4 main goals: (1) Explore the performance limits of Nb_3Sn accelerator magnets, (2) Develop and demonstrate an HTS magnet with a self-field up to 5T, (3) Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets, and (4) Address fundamental aspects of magnet design, technology and performance that could lead to substantial reduction of magnet cost.

The high field Nb_3Sn dipole development activity is broken down into two components. One is establishment of a baseline design to demonstrate feasibility based on the well-known cos-theta geometry using 4-layers to achieve a design field of approximately 15 T [54], Fig. 22. The second is aimed at higher risk innovative concepts to reduce cost and is based on the CCT concept to reduce cost and simplify fabrication [55], Fig. 23. The Nb_3Sn component is complemented by an aggressive program to develop magnets using both Bi-2212 and REBCO.

4. High temperature superconductors

Since the beginning of accelerator development, higher fields have always been a primary goal. The currently available high performance Nb_3Sn could lead to practical magnets operating around 16 T or with HTS inserts in a Nb_3Sn magnet to reach fields up to 20 T or more. Experience over the last two decades has shown progress toward achieving this potential but there are still many issues to overcome. One of the most onerous "features" of nearly every LTS magnet built, is training. When contemplating a future collider with more than 4 times the number of magnets, operating in the vicinity of twice the LHC dipoles, this becomes a great concern. Recent magnets, including an 11 T Nb_3Sn dipole and the IR quadrupoles under development by the US and CERN exhibit considerable training, and in some cases, detraining. These problems are not believed to be intrinsic and will likely be resolved relatively soon and for the current applications, some training is acceptable. As discussed above, in the case of the LHC Nb–Ti dipoles, there is retraining to cope with. This is clearly one of the major challenges for magnet developers. Another problem is the strain sensitivity of Nb_3Sn. An absolute upper limit for Rutherford cables in the LHC IR is 200 MPa with a target of 150 MPa. At high fields and hence, high stresses, very careful control of the pre-stress is necessary in order to avoid local stress concentrations but is not at all straightforward. Optimizing the cost/performance ratio highlights the need to stably operate as close as possible to the short sample limit. A typical margin for modern accelerator magnets is about 20% along the load line. This requirement substantially increases the quantity of conductor and hence the cost. The US MDP and EuroCirCol programs are targeting lower operating margins but have yet to be demonstrated.

As seen in Fig. 3, the two primary HTS conductors of interest, Bi-2212 and REBCO, have engineering current densities that are comparable to or exceed those of low temperature superconductors. For fields above 16 T, they are the only option. In addition to operating at very high fields at high current density the high temperature aspect also makes them very stable, and in some applications, creates the possibility of operating at high temperatures, reducing the cost and complexity of the cryo system. REBCO, like Nb–Ti requires no heat treatment, shifting the manufacturing risk up front. Despite this potential, each of them has unique challenges that must be overcome in order to build practical accelerator magnets. The problem at this time is cost. By any metric, HTS conductors cost many times that of Nb_3Sn. Part of this comes from the fact that they are still "boutique" conductors and are not produced in large quantity. Lack of an industrial market exacerbates this situation. It will be shown later that there are several ways to attack the problem. The high stability of the conductors poses difficulties in

Table 2
Comparison of Bi-2212 and REBCO characteristics.

	Bi-2212	ReBCO
Process	High temperature, high pressure reaction	Pre-reacted Tape
Scalability	Rutherford cables	Roebel, CORC®, Twisted Stack (Still in development stages)
Winding	Existing methods	Tape
Field orientation	Isotropic	Anisotropic
Mechanical properties	Poor	Relatively good compared to Nb_3Sn

detecting a quench and a reliable means to protect the magnet requiring new approaches. In the case of REBCO tapes, large magnetization effects are a challenge for dynamic field quality.

4.1. Conductor properties

A comparison of the two conductors is given in Table 2. Despite sharing the virtues of high current density and high upper critical fields, Bi-2212 and REBCO have little in common. REBCO is obtained by biaxial texture developed by epitaxial multilayer growth and is only available in tape that is anisotropic with respect to field orientation (about a factor of 5). Bi-2212 is available as isotropic round strand without macroscopic texture and in that respect, is similar to an LTS conductor.

4.1.1. REBCO

There are multiple vendors in the US, Japan, Korea, Russia and the EU that are producing REBCO. Many are produced on a Hastelloy substrate with a yield strength of 1 GPa. The J_c in the superconducting layer is very high and one of the goals to improve performance is to increase thickness of the superconducting layer to increase the engineering current density (J_e). It can survive bend radii less than 10 mm (depending on the thickness of the substrate). Thinner substrates also improve the J_e. Producing a single crystal in kilometer lengths without defects is an ongoing challenge. Wide filaments (4 mm) lead to magnetization effects that impact field quality. There have been some issues with debonding between the REBCO buffer layer and the substrate in epoxy impregnated magnets.

4.1.2. Bi-2212

Bi-2212 wire can be made in a variety of sub-element architectures with twisted filaments as small as 15 μm. Fabrication is via Powder In Tube (PIT) and is made in the same facilities as Nb–Ti and Nb_3Sn. The HEP SBIR program has helped develop improved powder that has significantly improved performance. Bi-2212 has the highest J_e of an HTS conductor and crosses over with Nb_3Sn at around 13–14 T. The reaction process, 890 °C in oxygen, is a challenge but has been successfully demonstrated on small solenoids and racetrack coils. It was discovered quite recently that a 50–100 bar over-pressure during the reaction process greatly enhances the performance [56,57]. Somewhat of a mixed blessing. Silver has a low elastic modulus (70 GPa) making the conductor strain sensitive. Not a good mechanical characteristic for high field magnets. However, there are promising magnet geometries and structures that could mitigate this weakness and there are R&D efforts to strengthen the material.

4.2. Quench detection and magnet protection

4.2.1. Quench detection

The large temperature margin of the HTS conductors leads to very stable operation that makes them virtually immune to training. The only reasons for an HTS magnet to quench are because it exceeds its critical current or there is a temperature increase due to a cryogenic failure or beam induced heat loads. Quenches below the short sample limit are due to flaws in the conductor and the magnet must be protected against these, but once a current limit is established, that level of performance should be reliably reached every time the magnet is powered. However, the virtue of stability makes quench detection challenging in HTS magnets because of slow propagation of the normal zone. In a magnet, traditional voltage-based detection may not be sensitive enough to prevent hot spot burn-out. Higher current density is also a mixed blessing. The consequently high energy density may exceed the heat capacity of the coil. The addition of copper to reduce the current density is not considered a good option. Fortunately, there are several solutions close to demonstration that could provide early detection which is the key to protecting the magnet.

Eigen Frequency Thermometry (EFT) is an active acoustic technique that can be used to monitor changes in the elastic modulus of an HTS coil due to temperature changes making the conductor a distributed temperature sensor [58]. Acoustic pulses are transmitted through the magnet by a piezoelectric transducer. Another transducer at the opposite end, monitors the acoustic signal. Despite the complexity of the acoustic signal it has a unique signature defined by the geometry and the temperature dependent elastic moduli of the magnet. Experiments have been successfully conducted on REBCO tapes and a prototype CORC® dipole. The technique was able to detect hot spots with a sensitivity of 1 K. The technique is undergoing further improvements and exploring the potential of using multiple sensor arrays for quench localization.

Another proposed technique to monitor and detect quenches in high current REBCO cables is by integration of optical fibers in the cable architecture using Rayleigh-backscattering interrogated optical fibers, resulting in a self-monitoring cable with both strain and temperature sensing capabilities as a function of position along the cable length and in time [59–61]. Work to date has been done under carefully controlled experimental conditions but there are plans to explore the technique in a more realistic environment.

Recently, LBNL has been investigating the feasibility of using capacitance probes to monitor the operation and detection of a quench for high-temperature superconducting accelerator magnets. The capacitance of a Bi-2212 racetrack coil package was monitored during various powering scenarios up to 8.5 kA at 4.2 K including current ramping at a rate varying from 5 to 200 A/s, and current dwells, and its effectiveness for quench detection has been compared with data obtained from an extensive array of voltage taps [62]. The measurement has shown that capacitance monitoring provides useful information for operation monitoring of superconducting magnets as well as being simple to implement. For example, the capacitance between the plate and the island of the racetrack coil is rather sensitive for detecting splice losses as small as 10 mW. The capacitance change is also sensitive to the index joule heating loss and therefore provides a rather early detection of quenches driven by localized heating, the primary mechanism for producing a quench in an HTS magnet system. Based on operational experience so far, capacitance measurement has been proven to be useful for monitoring the operation of Bi-2212 superconducting coils and shown to have potential for quench detection of magnets in general.

4.2.2. Magnet protection

Because of the high temperature margin and the subsequent low normal zone propagation velocity in REBCO conductors, quench heaters are not an option for protection of magnets with large stored energy. This is not all bad. Quench heaters add complexity and operational risk to the accelerator magnet system and a more robust technology would be welcome.

CERN has proposed using superconducting, low-inductance circuits connected in series with the magnet. When a quench is detected, the

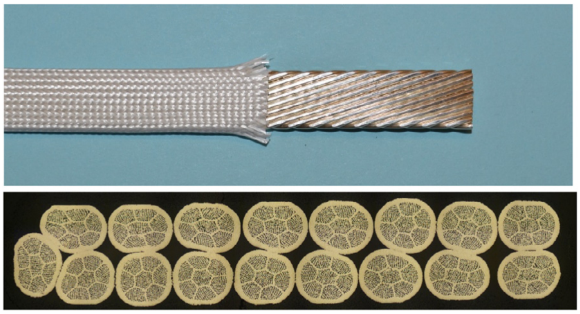


Fig. 24. Bi-2212 Rutherford cable.

Fig. 25. Roebel cable.
Source: Photo courtesy of CERN.

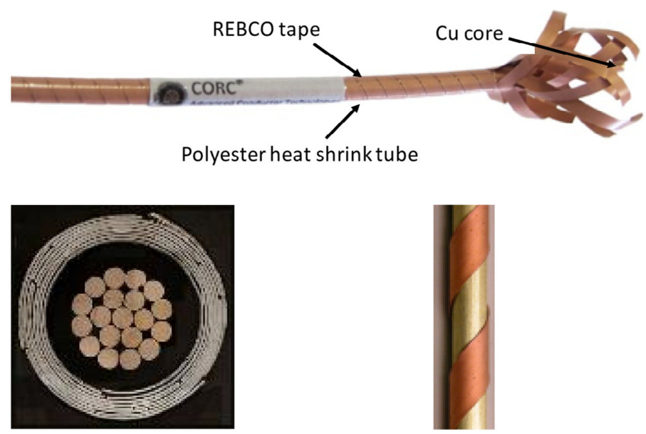


Fig. 26. CORC® cable.
Source: Photos courtesy of Advanced Conductor Technologies, LLC.

protection units are driven normal. Distributing several of these allows using a much higher extraction voltage while limiting the voltage to ground [63]. However, extrapolation of this technique for a string of magnets quickly becomes expensive and complex.

Another possible Detection/Protection technique is to time-average the voltage over a few seconds, removing the inductive voltage component using a bucking wire [64]. An electric field will be generated due to local heating near the quench current. Monitoring the current drift using this method allows more than adequate time for a slow extraction of the magnet stored energy. This promising technique certainly deserves further study. In the meantime, small R&D magnets can be protected simply by visually monitoring the voltage and manually ramping down the current.

4.3. Cables

Developing a viable HTS accelerator magnet critically depends on the availability of high current cables. Cables that can carry on the order of 10 kA will reduce the number of turns for lower inductance (lower coil to ground voltages) and reduce the conductor unit length. Long lengths without defects is currently an issue for REBCO. Current redistribution within the cable will mitigate the effects of periodic defects and reduce losses through transposition of strands. Other aspects of a viable cable are high engineering current density (current density averaged over the cable cross section), small bend radii without degradation, reproducible contact resistances and cooling.

As a round strand, Bi-2212 is easily made into Rutherford cable, Fig. 24. A packing fraction of approximately 85% maximizes the overall current density. The main drawback is the brittleness of the material itself. Cables start to show signs of degradation at about 60 MPa and magnet designs must take this into account. The main problem is heat treating a magnet coil at high pressure and very uniform high temperature.

REBCO presents a more difficult problem due to the high aspect ratio tape geometry. There are a number of cable designs currently under study. Two of the most promising candidates for accelerator magnets are discussed here. The first is Roebel cable, actually patented in 1914. The tapes are punched and interwoven to form a transposed cable (Fig. 25). The second option is Conductor On Round Core (CORC®), Fig. 26. This conductor circumvents the disadvantage of the tape geometry as the expense of some inefficiency in the use of conductor. It is very flexible and mechanically strong with little degradation. Challenges for both options are ensuring good current sharing at the terminations, degradation due to differential thermal contraction between the REBCO and epoxy used for impregnating the coils and minimizing transverse load effects.

4.4. Cost

HEP is not driving or leading the development of REBCO, which is primarily driven by large industrial markets in MRI, fault current limiters, transmission lines, motors and generators. However, the DOE OHEP and EERE are supporting further improvement in conductor performance that will improve the cost/performance ratio. It is expected that improved conductor performance and lower cost HTS will be seen in the next 3–5 years.

At this time the relatively high conductor cost is an obstacle to the otherwise potentially rapid development and demonstration of HTS magnets. Worldwide, 15 vendors are competing to supply commercial REBCO tapes with piece lengths ranging from a few hundred meters to a few kilometers. There is currently only one producer of Bi-2212 strand but at least two powder providers in the US. REBCO is approaching continuous lengths up to 4 km. Development of cables with current sharing (necessary for high current cables in any case) would mitigate the requirement for long lengths and reduce the cost. Bi-2212 strand lengths are essentially limited only by billet size. There is plenty of low-hanging fruit for improving performance and lowering cost for both Bi-2212 and REBCO conductors. The engineering current density, in-field performance, cost, yields and lengths of REBCO continue to improve year to year by large factors (up to X10 in performance are now in the R&D pipeline). Thus, the opportunity for improvements in accelerator magnets will continue to grow and a successful demonstration of the use of HTS by HEP (or any other application, e.g. fusion) would benefit and encourage adoption by industry.

The DOE Office of Fusion Energy Sciences (FES) has recently published a report on Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy [65] where HTS is called out as one of four "most promising transformative enabling capabilities for the US

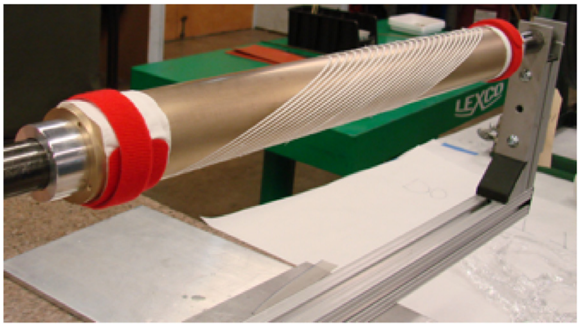


Fig. 27. Bi-2212 CCT coil ready for heat treatment.
Source: Photo courtesy of T. Shen, LBNL.

to pursue that could promote efficient advance toward fusion energy". This is good news for both programs. Many of the goals, for example, development of high current cables, have strong overlap and will increase the opportunities for further development of the technology. Other applications outside HEP and Fusion Energy Science such as ion sources, undulators for light sources, gantries for particle therapy, high field NMR, 25 T solenoids for x-ray and neutron facilities and wind turbines could all contribute to generating a sustainable industry.

5. HTS programs

There has been considerable work done in the past on HTS magnet R&D but it has largely been limited to solenoids until recently. The relatively near-term improvements in HTS materials has spurred a greater interest and some programs are now taking up the challenge to develop accelerator magnets. HTS could be used for insert coils to boost the field of Nb_3Sn outserts or in all-HTS magnets, the latter being more expensive but unhampered with operational issues that hybrid magnets would have, e.g. quench protection, increased mechanical complexity and operating temperature limitations.

The HTS program at BNL has produced a number of small coils using both Bi-2212 and REBCO. A unique aspect is the attempt to use react and wind for Bi-2212, a challenging but potentially interesting approach. The program has wound a number of high field REBCO racetrack coils and solenoids using single tapes.

As part of the US MDP, LBNL is developing high-field Bi-2212 and REBCO accelerator magnet technology. The Bi-2212 magnet development program is based on small racetrack and CCT coils. Racetrack coils, incorporating a 50 bar over-pressure heat treatment, have reached over 80% of the predicted short sample limit, a significant improvement over similar attempts several years ago. True to the promise of HTS, the coils did not quench due to mechanical motion or epoxy cracking [66,67]. Plans are to combine two racetracks into a dipole configuration. In parallel with the racetrack program, CCT coils have been fabricated and will be overpressure heat treated and tested soon [68], Fig. 27.

As discussed above, despite many virtues, REBCO is a challenging conductor to work with. The tape geometry does not lend itself easily to the winding geometries needed for accelerator magnets and it is difficult to retain reasonable current densities in a cable with an acceptable bend radius. The MDP at LBNL uses a combination of the CCT that has a favorable winding configuration with CORC® cable. A relatively simple double-layer three-turn CCT dipole magnet was recently built and tested at 77 and 4.2 K [69], Fig. 28. As simple as the approach was, it still allowed development of winding techniques, joints and testing with a small amount of the very expensive conductor. The successful test was an important step toward the ambitious goal of producing a REBCO dipole in a compact geometry that could achieve 5 T in a background field of 16 T. It will be necessary, but nonetheless it appears feasible, to increase the engineering current density and decrease the bending radius of the CORC cable to 15 mm.

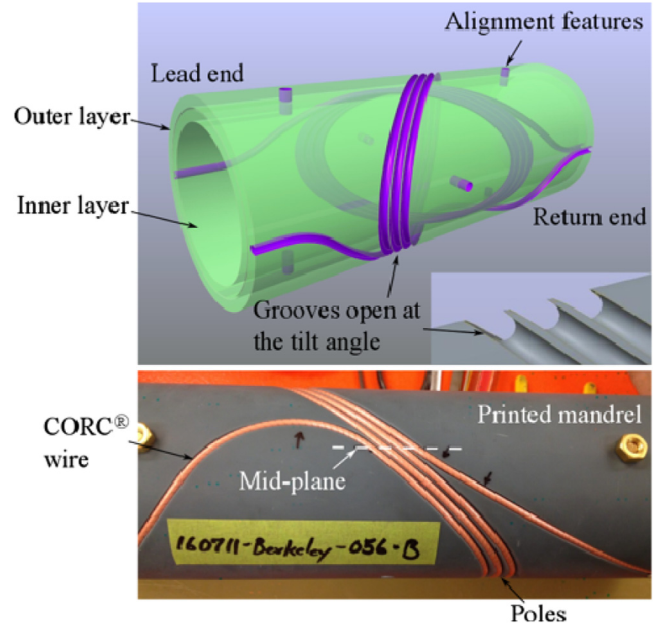


Fig. 28. Top: a 3D model of the assembled CCT magnet coil, designated C0a. The inset gives a close-up of the "U"-shaped grooves. Bottom: the outer layer of C0a. The white dashed line illustrates the mid-plane of the magnets. The bottom pole region is also shown.
Source: (Graphic courtesy of X. Wang, LBNL.)

The EuCARD-2 project [70], aims at exploring accelerator magnet technology for 20 T operating field, clearly in the realm of HTS. In cooperation with the US MDP and Japan the program is initially focused on the development of a 10 kA-class superconducting, high current density cable suitable for accelerator magnets that will result in a 5 T stand-alone dipole of 40 mm bore and about 1 m length. This magnet could then be inserted into a large bore dipole, achieving a field of 18 T or more. The first high current HTS coil, Feather-M0.4 containing Bruker Tape and KIT Roebel cable has been powered above 12.9 kA in 25 K gas and quenched over 100 times without degrading the coil [71].

Feather M2.1-2 is one of the first high temperature superconducting dipole magnets in the world. It reached a field of 3.1 T at 5.7 K. No degradation occurred during winding, impregnation, assembly and cool-down of the magnet. The magnet was quenched numerous times by exceeding the critical current and no degradation or training was evident. There are still challenges to face as the program moves forward: detecting quenches with the magnet fully submerged in liquid helium, the high current HTS joint design and operation, operating in high external magnetic field and finally controlling magnetic field-quality using the 5 mm wide tapes.

6. Conclusions — moving to a new paradigm

Though it has taken more than half a century to develop the technology we have now, much has been learned. Tools, materials and infrastructure that were not conceived of a few decades ago are now available. The community is ready to take on the challenges necessary to realize the potential of HTS. Aggressive development programs are on the verge of demonstrating technological feasibility that will create and help drive a sustainable market from which to leverage. Development of high current cables and exploration of new magnet geometries to accommodate and exploit the unique characteristics of the HTS conductors is critical. The book on LTS magnets has nearly reached the denouement. The story of HTS will be an exciting one but we are only on the first chapter.

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